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Rocket Test Facility
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NOTICES

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ABSTRACT

The characteristics of the arc in a d-c arc plasma generator having a Gerdien-type electrode configuration are described. Particular emphasis is placed on the jet structure and its influence on the use of this type of generator as a research, hot gas source. A complete explanation of the experimental methods used to determine the true arc configuration is included. These methods consisted of probe studies, high-speed photographs, and various electrode configuration studies. The investigation was made in a low pressure test cell and at atmospheric pressure.

The results show that at atmospheric pressure the observed flame exiting from the generator orifice is in reality the envelope of many blown arcs. In the low pressure test cell, the expanded flame is found to be free of these blown arcs; instead the arc is contained in a small section near the orifice exit.

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TABLES

ILLUSTRATIONS

NOMENCLATURE

A	Cross-sectional area, cm^2
E	Work, erg
e	Electronic charge, coulomb
I	Current, amp
I_{es}	Probe electron current, amp
I_p	Ion current, amp
I_{ps}	Probe ion current, amp
I_s	Probe current, amp
J	Current density, amp/cm^2
J_{ep}	Plasma current density, amp/cm^2
J_{es}	Probe current density, amp/cm^2
k	Boltzmann's constant
N	Number density of particles, $number/cm^3$
p_c	Test cell pressure, mm Hg
S	Slope of data curve
T	Temperature, °K
T_e	Electron temperature, °K
V	Electric potential, volt
$\bar{v}$	Average velocity, cm/sec
λ	Mean free path, cm

INTRODUCTION

In many areas of research the plasma generator having the Gerdien electrode configuration is used as a source of hot gas. The use of equilibrium dependent spectrometric methods, electrical probes, and other methods of measurement of the gas properties in the flame exiting from this plasma generator has prompted the assumption of equilibrium and/or current free conditions in the flame. Therefore, knowledge of the true arc and flame structure has become increasingly important.

A research program into methods of spectrometric measurements of the properties of gases at high temperatures at the Rocket Test Facility (RTF), Arnold Engineering Development Center, Air Force Systems Command (Refs. 1 and 2), resulted in the design and fabrication of a plasma generator having the Gerdien electrode configuration. Application of various experimental and mathematical methods (Refs. 2 and 3) to the plasma flame yielded average gas temperatures on the order of 15,000°K. However, a method of simple energy balance in the plasma generator system indicated a maximum average gas temperature on the order of 6,000°K. Since no error could be found in either method, attention was turned to the assumption of thermal equilibrium in the gas stream. If thermal equilibrium does not exist in the ionized gas stream, application of the spectrometric method is precluded, in that temperature in nonequilibrium systems is not defined. [Other investigators (Refs. 4, 5, 6, and 7) have considered the plasma flame to be an ionized gas in thermal equilibrium.]

This report describes a series of experiments designed to give positive information about the electrical structure of the jet and thereby to show at what conditions the plasma flame can be considered to be in a state of thermal equilibrium. Identical experiments were performed for the case of the plasma exhausting into atmosphere and the case of the plasma exhausting into a low pressure vessel. The experiments performed are described, and the individual results are presented. Some general results are then inferred from the individual experiments. Finally, some conclusions are drawn concerning jet electrical structure for both the atmospheric plasma flame and the low pressure jet, and an interpretation concerning thermal equilibrium is made.

Because the terms plasma and arc are referred to throughout this report, they are defined here for purposes of clarification. Plasma is

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defined as an ionized gas which is electrically neutral; that is, the net electrical charge is zero. An arc cannot be so clearly defined. However, for the purposes of this report, an arc is considered to consist of a conducting path (in a gas) having a high current density and a high electron temperature.

DESCRIPTION OF APPARATUS

PLASMA GENERATOR

~420°K to 3500°K in Air.

The plasma generator used in all the experiments described in this report employed the Gerdien-type electrode configuration. The operating range was from 4 to 50 kw with chamber pressure ranging from 1.0 to 2.5 atm. The enthalpy of the gas ranged from 100 to 1000 cal/gm. A detailed analysis of the operating characteristics is given in Ref. 1, and a cross-sectional view is shown in Fig. 1. Figure 2 is a photograph of the plasma generator and actuating mechanism. The orifice electrode used in these experiments was made of graphite, and a 1/4-in.-diam orifice was used.

VACUUM CELL

The vacuum cell was designed and constructed at the Arnold Center. It is a cylinder 8 ft long and 3 ft in diameter. The RTF exhauster system (Ref. 8) in combination with an air ejector provides a cell pressure of 0.2 mm Hg with zero secondary flow and will provide a cell pressure of 0.55 mm Hg during a typical run made with a secondary flow from the plasma jet of approximately 5 gm/sec.

EXPERIMENTAL APPARATUS AND INSTRUMENTATION

Various measuring devices and probes were used in the experiments. The probes are described in the appropriate sections and are shown pictorially in Fig. 3. Other instrumentation consisted of oscilloscopes, precision potentiometers, meter shunts, and electrical meters.

EXPERIMENTAL PROCEDURE AND RESULTS OBTAINED AT ATMOSPHERIC PRESSURE

The work on plasma diagnostics reported in Refs. 1, 2, and 3 was performed with the plasma jet exhausting into the atmosphere. At this condition the plasma flame appears to the eye as a highly luminous jet about 1-1/2 in. long; if a welding glass is used to view the jet, a brilliant cone about one-inch long is seen surrounded by a sheath of less luminous gas. This jet is very convenient for spectrometric measurements. However, the discrepancy between the temperature of the plasma found by the spectrometric method and by an energy balance method gave rise to the suspicion that some nonequilibrium mechanism of energy transfer to the gas was present. Therefore, two possible arc mechanisms within the plasma generator were hypothesized and are illustrated in Figs. 4a and b. In Fig. 4a the arc, because of the gas flow, is blown outside the orifice and forms small, high current-density channels which move about at a high frequency. In Fig. 4b the arc attaches itself uniformly around the inner part of the orifice, and the gas passing through the arc produces a current-free plasma flame on the outside of the orifice. 12

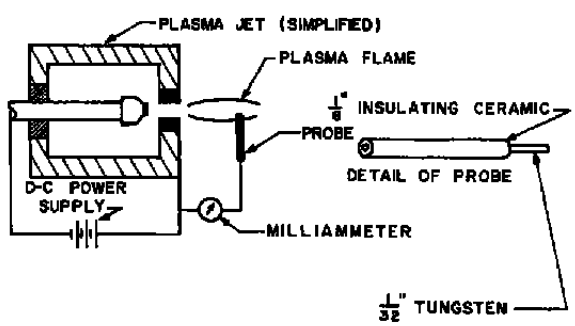
HIGH SPEED PHOTOGRAPHS

If arc channels are assumed to exist outside the orifice, high speed photographs should reveal the channels or their fluctuations. Therefore, photographs were taken at framing speeds varying from 2.0×10^4 fps to 0.5×10^6 fps. A sequence of photographs taken at this latter frequency is shown in Fig. 5. Although no definite arc channels can be seen in the photographs, it is obvious that fluctuations in the jet pattern did occur. Since the photographs did not produce results which could be interpreted, other experimental procedures were necessary in order to obtain a better description of the flame mechanism.

ELECTRICAL PROBE STUDIES

Current Probes

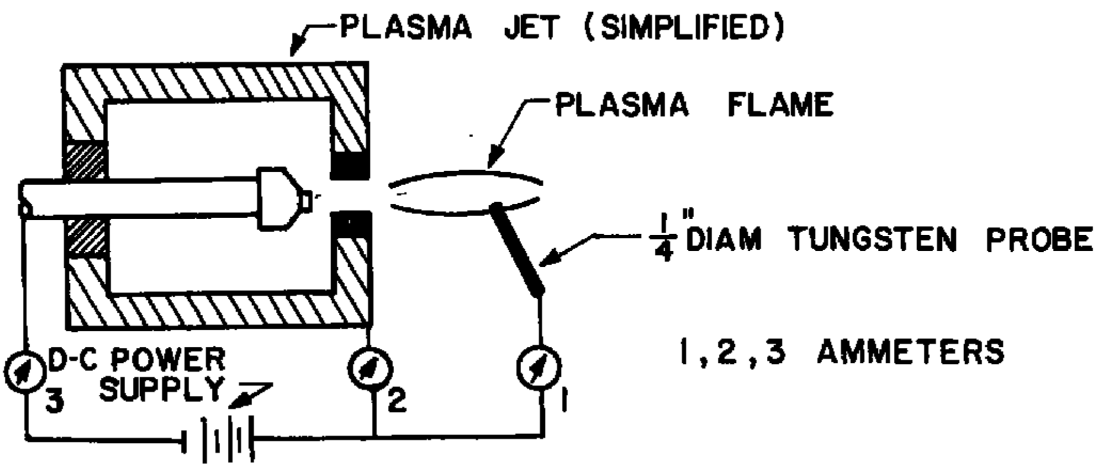
The first new approach was the use of an electrical probe to check the hypothesis illustrated by Fig. 4a. The study consisted of mapping the shape of any current paths that might exist outside the orifice using the probe circuit shown in Schematic I. (The probe consisted of a length of 1/8-in.-diam insulated tungsten rod, Fig. 3a.) The procedure was to adjust the depth at which the probe was inserted into the flame at points along the axis to obtain a constant current.



SCHEMATIC I

The data from this experiment are shown in Fig. 6 in terms of constant probe current as a function of probe position. Special note should be made of the smooth appearance of the plot; the bluntness on the end implies the possibility that this may be the turning point of the blown arc channel. The most significant fact determined from this experiment was that an appreciable current could be made to flow through the probe circuit.

It was noted that higher currents could be detected nearer the plasma flame center by inserting the probe deeper into the flame and that the heat transfer to the probe was not sufficient to cause melting in time increments on the order of several seconds. Therefore, an alternate to the experiment of Schematic I was suggested. The circuit of Schematic II was the same as shown in Schematic I, but the probe was uninsulated, as shown in Fig. 2b. Three ammeters were used to



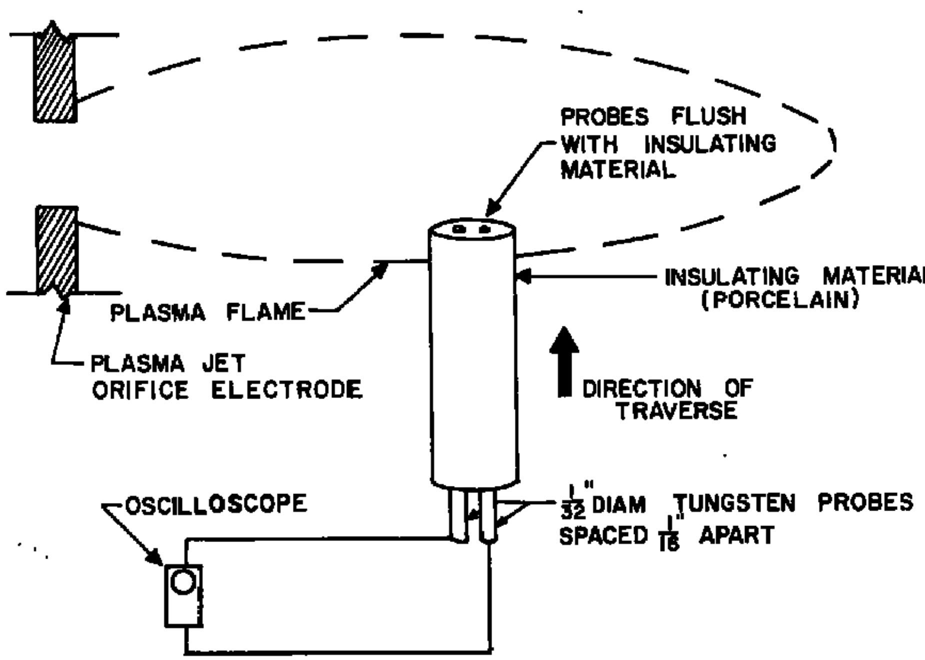
SCHEMATIC II

determine whether the probe current was coming from the inner or the orifice electrode. If the hypothesis of Fig. 4a were correct, then the probe should interrupt the blown arc current paths and provide a parallel electrical path back to the orifice anode. The probe tip was placed near the center of the plasma stream for these experiments. (Meters 2 and 3 actually consisted of current shunts, and the millivolt readings were made with precision potentiometers in order to obtain the desired readability. The probe current was read with an ordinary ammeter.) When this experiment was performed, the probe current (ammeter 1) varied from zero at the flame tip to seven amperes when the probe was 0. 10 in. downstream of the orifice exit. At each point it was found that the sum of the currents in ammeters 1 and 2 was equal to the total current in ammeter 3. A plot of these data is shown in Fig. 7, and an example of the data is shown in Table 1. The significance of the result was the fact that the large currents detected in the flame were shown to be the result of splitting the orifice electrode current and the fact that the insertion of the probe did not alter the operating characteristics of the plasma generator. This experiment strongly indicated the possibility of the existence of a blown arc; it did not necessarily prove the existence of a pattern such as that hypothesized in Fig. 4a.

Another interesting phase of the experiment made with the probe circuit of Schematic II involved measuring the probe current as a function of gas flow. Reference 1 showed that when the gas flow of the plasma generator was increased, the total electric current to the plasma generator system decreased. Therefore, it would be expected that the probe in the plasma stream would draw less current as the total current decreased. However, when this experiment was performed with the probe 1/2-in. downstream, it was found that as the gas flow increased ~~and the total current~~ *) decreased the probe current increased. This result definitely showed that the action of the increased gas flow forced the blown arc still farther outside the orifice electrode when the flow was increased.

Double Probe

To substantiate the data so far obtained, that is, to establish that the probe of Schematic II was not simply immersed in a conducting medium but was actually interrupting current paths, a third experiment (Schematic III) was conducted. The probes (Fig. 3c) were inserted into the



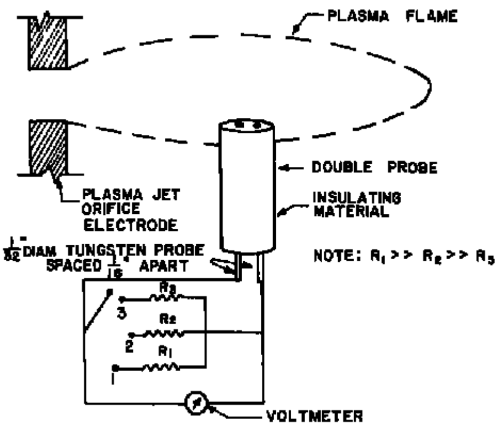
SCHEMATIC III

*) just an increased number of electrons per second reaching the probe, due to higher air speed ?

stream (oriented as shown in Schematic III), and the voltage between the probes was recorded on an oscilloscope. A traversing mechanism allowed the probe to be quickly passed through the stream so that the small probes did not melt. A potentiometer was attached to the traversing mechanism, and the signal generated by it was used to deflect the oscilloscope horizontally. The potential between the probes caused a vertical deflection of the oscilloscope spot so that it traced out a plot of probe voltage as a function of position within the plasma flame. The experiment is based on the hypothesis demonstrated in Fig. 4a. If the arc paths were outside the orifice, the double probe in its traverse could first interrupt current flow in one direction and then in the opposite direction. The probe in its traverse would thus register a potential on the oscilloscope in first one direction and then in the other. The results of this experiment are shown in Fig. 8. Vertical positive deflections indicated a difference of potential between the two probes, the higher potential being nearest the orifice electrode. For the data shown in Fig. 8b, the traverse time was on the order of two seconds. From the trace it is seen that the polarity reversed many times, an indication of rapid movement of the blown arc relative to the axial centerline of the flame.

Although the double probe experiment strongly substantiated the hypothesis illustrated by Fig. 4a, some consideration was given to the validity of the double probe experiment. The double probe technique shown in Schematic III was based on the interruption of a current path or arc path by the double probe and on the fact that this was equivalent to placing the two probes across a small section of the arc or across a resistance containing a flow of electric current. To investigate the validity of the double probe, consider Schematic IV. In this circuit if the arc resistance, R_p, is connected with a parallel resistance, R_3, the voltmeter reading is given by

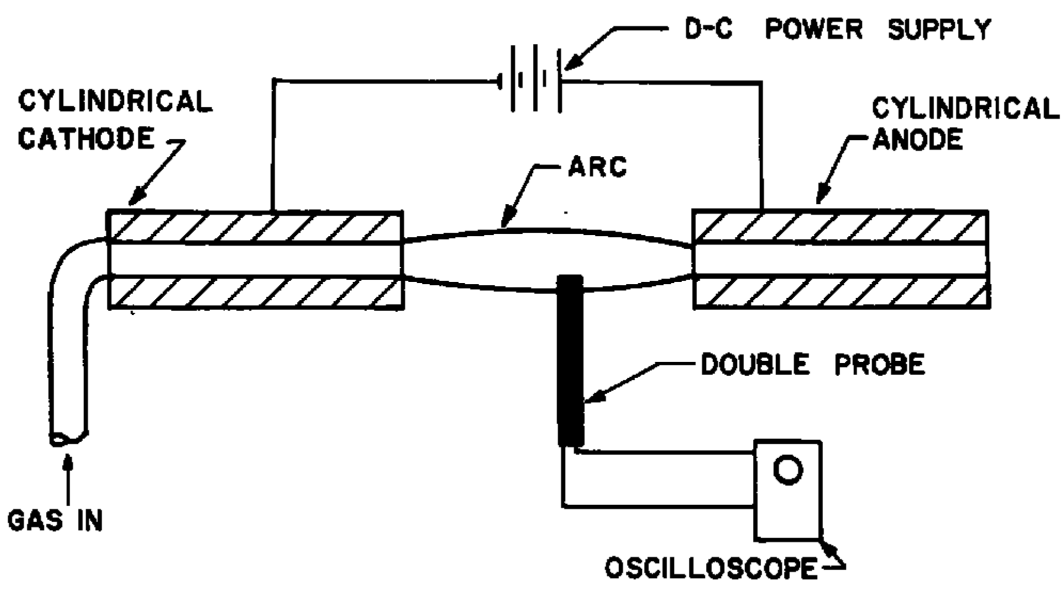
$$V = I \frac{R_p R_3}{R_p + R_3}$$



SCHEMATIC IV

If now R_1 is changed to R_2 where $R_2 \gg R_1$, the value of the total circuit resistance will increase. If then R_n is, in fact, a resistance, there will be a corresponding increase in the voltmeter reading. However, if between the two probes there is a pure emf source of some kind, there must be no change in the voltmeter reading. Data from this circuit for $R_2 = 7.5 \times 10^3\,\Omega$ gave a voltmeter reading of $V = 0.05$ volt, for $R_2 = 3.3 \times 10^4\,\Omega$, $V = 0.06$ volt, and for $R_2 = 1.1 \times 10^6\,\Omega$, $V = 0.08$ volt. From these values, it is seen that as the parallel resistance increased so did the voltage drop between the probes. Therefore, the arc may be considered as a series of small resistors, and the double probe technique is valid.

A study to give a better understanding of the double probe technique was made by considering the experiment illustrated in Schematic V. Here the direction of current flow and potential distributions of the arc



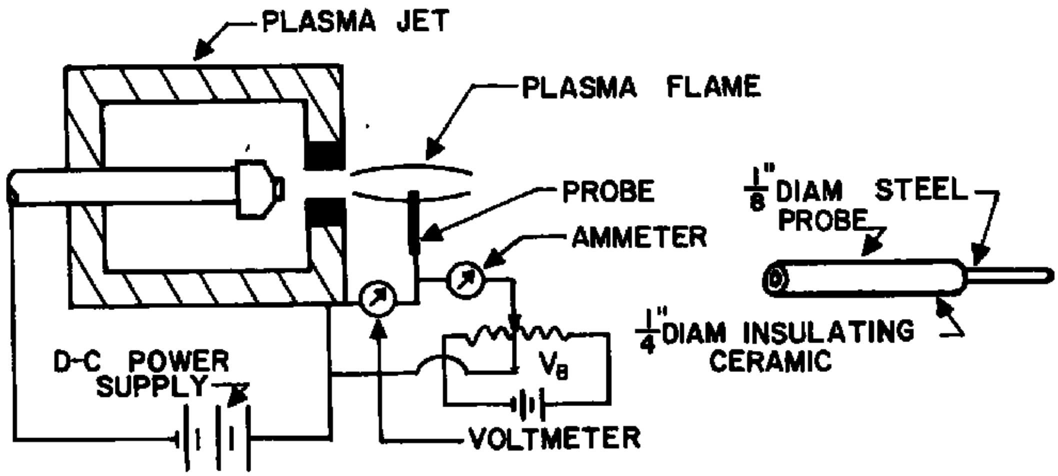
SCHEMATIC V

discharge were known. Therefore, it should be quite easy to interpret the results of a probe oscilloscope trace. Oscilloscope traces from this circuit (shown in Fig. 9) were always positive, an indication that the current flow was from cathode to anode, which agrees with the way the circuit was set up and shows that the double probe correctly defined the direction of current flow in the arc discharge.

The circuits of Schematics III and V were also used in attempts to define the frequency characteristics of the oscillations shown in Fig. 8 by holding the probe stationary and displaying-the trace as a function of of time on the oscilloscope. The results of this investigation indicated that the frequency of the oscillations was completely random and greater than 10 mc. The significant point here is that the arc is a non-steady process at a very high frequency.

Langmuir Probe

A classic method of investigating electric discharges in gases is by the use of Langmuir probes (Refs. 9, 10, 11, and 12). Application of the Langmuir probe circuit to the plasma generator system is illustrated in Schematic VI. A complete discussion of the probe theory is given in Appendix A.



SCHEMATIC VI

From the theory given in Appendix A, a plot of the logarithm of current density as a function of probe potential should yield a curve with a straight line section in the negative region which becomes concave downward as the probe potential approaches zero and becomes constant as the probe becomes positive if the flame is in thermal equilibrium. The straight line section satisfies the Boltzmann equation

$$J_{es} = J_{ep} \exp\left(-\frac{eV}{kT}\right)$$

and is a necessary condition for thermal equilibrium to exist in the ionized gas stream.

The degree of equilibrium of the plasma flame was investigated using the Langmuir probe theory. A typical set of data is shown in Fig. 10. Here, a plot of I_s vs V is shown for a probe immersed in the edge of a plasma flame (see Ref. 11 for an interpretation). Thus I_s is the current to the probe, and V is the probe potential. It was noted that as the voltage was changed in the negative direction, beyond -8 volt, the probe became a reflector of electrons, and the current became slightly negative as a result of the impingement of positive ions. The current approached a negative constant value, I_{ps}, as the potential was increased negatively. At -8 volts there was a sudden increase in current; this is the point at which the faster electrons begin reaching the probe. At $I_s = 0$ the electrons arriving at the probe are equal to the total charge of the ions arriving; at voltages greater than -8 volts and less than zero volt the current measured is the electron current, I_{es}, which is computed for purposes of calculation by

$$I_{es} = I_s + I_{ps}$$

and is the total electron current to the probe. It is this region (-8 volts to 0 volt) that is of interest, and data were taken for a plane probe immersed in the plasma at various points within the stream. These reduced data are shown in Fig. 11. Note that as the probe proceeded into the stream the data deviated more and more from the straight line criteria of the Boltzmann equation, an indication of nonequilibrium in the center section of the flame. Although the data indicated the possibility of equilibrium in the outer portion of the flame, it must be remembered that the mean free path of the electrons at atmospheric pressure ($\lambda \approx 10^{-4}$ cm) is much smaller than the probe diameter. Therefore, consideration must be given to possible disturbing effects of the probe on the plasma, and quantitative results would not be expected to be accurate.

Assuming the arc structure of Fig. 4a where the greater portion of the blown arc is in the center section of the flame and the rapid movement of the arc makes the outer portion of the flame not quite so unstable, certain predictions as to Langmuir probe data can be made. If the probe is immersed in the outer edges of the flame, a reasonable approximation to a Maxwellian distribution should be observed. However, as the probe proceeds into the flame, thus interrupting the nonequilibrium arc paths, deviation from a Maxwellian distribution should increase. The data in Fig. 11 show that this prediction holds. Curve one is very nearly a straight line and the data were taken at the flame edge. However, as the probe moved into the flame in 1/32-in. increments, the deviation from a straight line (or Maxwellian distribution) increased. From this and proceeding experiments then, it appears that the arc is not only blown outside the orifice anode but is, for the most part, contained in the center portions of the flame, as assumed in Fig. 4a.

PLASMA GENERATOR POLARITY

When the plasma generator was first operated (Ref. 1), it was noted that much more stable operation could be obtained with the orifice electrode polarity positive and the inner electrode polarity negative. Figure 12 shows two photographs of the plasma generator operating; Fig. 12a shows normal operation (orifice electrode positive), and Fig. 12b shows the plasma generator operating with the orifice electrode negative. Both photographs were taken with identical camera settings and camera position and with the plasma generator operating equipment set at identical values. With the orifice polarity positive (Fig. 12a), the electron current flow was from the inner electrode to the orifice electrode and in the same direction as the gas flow. However, with the orifice electrode negative (Fig. 12b), the electron current flow was opposite to the gas flow. In Fig. 12b the action of the gas flow has forced the arc farther outside the orifice, and part of the arc has attached itself to the face of the orifice electrode. This attachment is seen as a lump at the bottom of the flame in Fig. 12b. Special note should be taken of the length of the flame shown in Fig. 12b; it is approximately two inches long as opposed to one inch for the plasma jet in normal operation (Fig. 12a). This phenomenon gives still further support to the hypothesis illustrated in Fig. 4a. The attachment of the arc to the orifice face shows that electrons are emitted at this point and then move against the action of the gas flow to the inner positive electrode. However, in the process of moving to the inner electrode, the electrons are blown downstream, and thus the flame length is longer than the flame obtained when the generator is connected for normal operation.

INTERNAL ARC

A final observation on the atmospheric plasma flame was concerned with the structure of the internal arc, that is, with the section of arc from the inner electrode to the inner part of the orifice electrode. Normally, this section of arc cannot be observed. However, at Arnold Center a plasma generator was constructed with a cylindrical glass body. It was then possible to photograph the internal arc at normal operating conditions of the plasma generator, as shown in Fig. 13. The diameter of the orifice is shown, and the inner electrode is visible. The direction of gas flow was from left to right. Note how the action of the gas flow and the self-induced ~~electric~~ magnetic field has constricted the arc so that its diameter is smaller than the orifice and is centered in the orifice entrance. No apparent attachment to the orifice can be detected. This is the expected arc configuration if the blown arc theory is valid.

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EXPERIMENTAL PROCEDURE AND RESULTS OBTAINED AT LOW PRESSURE

The results of the studies of the atmospheric plasma flame indicated a very complicated electrical structure within the jet. Therefore, results of spectrometric measurements might be in serious error. One method of studying the blown arc problem was thought to be an expansion of the gas jet in a low pressure test cell and an investigation of the expanded jet. However, in order to justify this procedure it was necessary to examine the expanded jet in the same way as the atmospheric jet had been examined. Figure 14 is a photograph of the plasma jet exhausting into a test cell pressure of 0.55 mm Hg. For clarity, the two portions of the flame were named. The bright section at the orifice exit was called the hot core, and the downstream luminous section was called the expanded flame.

ELECTRICAL PROBE STUDIES

Current Probes

To investigate the structure of the expanded flame, a plot of constant current values as a function of probe position relative to the flame centerline was made. This experiment utilized the probe shown in Fig. 3a and the circuit of Schematic I. The data points are shown superimposed on the photograph in Fig. 15. Each dot on the photograph represents a probe position for which a current value of 2.0 milliamperes was obtained. As the probe was inserted into the stream center at each position, the probe current increased. This increase at the stream center was found to be a maximum of one amp at a position 1/8 in. downstream from the orifice, 75 milliamperes 6 in. downstream, and 14 milliamperes 12 in. downstream. The normal shock wave occurred about 4 in. downstream of the orifice exit, and it was found that in this shock wave a current of 210 milliamperes could be detected by the probe. On the upstream side of the shock wave, the current to the probe was 65 milliamperes; on the downstream side, it was 100 milliamperes. The data are shown in Table 2.

The plot in Fig. 15, although smooth, does not have the same shape as the similar plot of the atmospheric plasma flame but seems to follow the supersonic flow streamline. This is perhaps indicative of the measure of the conductivity of the ionized gas stream. The significance of this measurement is that the data are not at all similar to equivalent data taken from the atmospheric jet. Also, the value of the current that can be detected at any position in the expanded jet is very small compared with the total arc current.

The probe circuit illustrated by Schematic II was used with the tungsten probe (Fig. 3b). Here the probe collecting area was much larger than the collecting area of the probe of the previous experiment and would, therefore, draw a larger value of current. Thus, this circuit is, perhaps, a better method of investigating the structure of the expanded flame when it is used with the probe shown in Fig. 3b. In this experiment, as in the same experiment on the atmospheric pressure plasma flame, the probe current was measured as a function of distance downstream. The results are shown in Table 3 and are of great interest in that very little change could be detected in the probe current as the probe was moved downstream. This is a definite indication that the blown arc does not exist in the expanded flame. However, when the probe was placed in the hot core section, the data were in the same range and similar to the data taken from the atmospheric plasma jet. This is a strong indication that the blown arc is contained only in the hot core.

Double Probe

The double probe experiment (Schematic III) was also utilized to study the expanded jet. Figure 16 is a plot of the potential between the double probes as a function of the probe position relative to the gas stream centerline. The data were obtained at a plane approximately 4 in. downstream of the orifice exit. Particular note should be taken of the fact that the potential was at all times in the same direction, that is, any current paths in the gas stream were all in the same direction. The polarity reading on the voltmeter (which was substituted for the oscilloscope in this experiment) was set up so that a voltage drop in the direction downstream of the orifice caused a positive deflection. Obviously, then, any current paths in the expanded stream were moving in one direction. When the double probe was inserted into the hot core section, it was observed that the potential reversed many times, an indication that in this section of the flame the blown arc existed in much the same manner as in the flame of the atmospheric jet.

(A voltmeter was used in place of an oscilloscope in the preceding experiment because of the high level of electronic noise in the evacuated test cell. The flame did not have a detrimental effect on the probe because of the much lower temperature of the expanded flame compared with that of the atmospheric pressure plasma flame.)

Langmuir Probe

The Langmuir probe (Appendix A) was applied to the plasma jet exhausting to low pressure (Fig. 14). The probe was immersed in the plasma flame at various points to determine when the data would satisfy the Boltzmann equation and therefore would define sections that might be in equilibrium and current-free. Figure 17 is a plot of the reduced data from the Langmuir probe circuit of Schematic VI. Curve number 1 in Fig. 17 is of particular interest because these data were obtained from the probe immersed in the hot core. The curve does not exhibit a characteristic as predicted by the theory (Appendix A) and therefore does not satisfy the Boltzmann equation. Thus, there is a departure from equilibrium among the electrons in the hot core. Each of the other curves, however, has straight line sections, an indication that the Boltzmann equation is satisfied in that particular region. This is a necessary but not sufficient condition for equilibrium in the ionized gas stream.

PLASMA GENERATOR POLARITY

The final phase of experimentation with the plasma jet exhausting to low pressure consisted of reversing the polarity of the power supply. In normal operation (Fig. 18a), the orifice electrode of the plasma jet was positive, and electrons traveled from the inner electrode to the orifice electrode in the same direction as the gas flow. In Fig. 18b the generator was operating with the orifice electrode negative, and part of the arc had attached itself to the outer face of the orifice electrode. From these photographs it was seen that when the orifice polarity was negative the flame was longer and wider than the flame which existed when the orifice electrode was positive. The action of the gas flow, then, caused the arc to be forced farther downstream and provided a large hot core section.

DISCUSSION

The experiments described in the previous sections were each designed to contribute some significant information about the electrical structure of the plasma flame. Therefore to discuss the experiments in the section on atmospheric plasmas, a mechanism of arc structure was assumed and then examined on the basis of the experimental results. Consider Figs. 4a and b. In Fig. 4b the arc is attached to the inner part of the orifice, and the gas passing through the arc produces a current-free plasma flame on the outside of the orifice. In the ideal case, the plasma would be in equilibrium at atmospheric pressure. In the second configuration (Fig. 4a), the arc, because of the gas flow, is blown outside the orifice and forms small high current-density channels which move at a high frequency. This configuration would not be expected to conform to an equilibrium plasma. The experiments were designed to check the validity of these hypothetical assumptions.

ATMOSPHERIC PRESSURE

The high speed photographs in Fig. 5 pointed out the need for probe studies. These photographs showed that if the arc were blown outside the orifice the frequency of its movement was too great to be shown, even at camera speeds as high as 0.5×10^6 fps.

The probe studies were much more informative. A probe study utilizing Schematic I mapped the shape of a constant current envelope. This current contour (Fig. 6) was approximately the same shape as the observed plasma flame, leading to the conclusion that perhaps this current contour was the envelope of the blown arcs and that the hypothesis of Fig. 4a was correct. The envelope of blown arcs, because of the breaking up of the arcs at the end of the flame, should have a higher current density at the center of the envelope and at the orifice exit than at the end of the flame. This theory was found to hold when the circuit in Schematic II was used. The plot of the current to the probe as a function of distance downstream of the orifice exit (Fig. 7) showed that as the probe moved downstream, thus interrupting fewer and fewer current paths or arcs, the current decreased in nearly a linear fashion until the probe reached 0.4 in. downstream. At this point, the curve began to decrease by a far lesser amount, an indication that the probe was now beyond the arc paths and was in a conducting ionized gas.

The hypothesis in Fig. 4a was further verified by proving that the current paths actually existed. Schematic III (double probe) provided a method whereby it could be shown that each arc path could be located by the drop in potential in the direction of current flow within the path. The reversal of polarity between the probes clearly showed that there were current paths in both directions. The only explanation for this was the loop arc (Fig. 4a).

Photographs taken of the plasma flame (Fig. 12) in normal (orifice electrode positive) operation and with the orifice electrode negative showed that the action of the gas flow blew the arc still farther downstream when the orifice electrode was emitting the electron flow.

The application of the Langmuir probe theory to the atmospheric plasma flame gave an indication of the location of the blown arc with respect to the stream centerline. With the probe in the outer portion of the stream, a Maxwellian distribution of electrons was noted. However, as the probe moved into the stream, deviation from the Maxwellian distribution became greater. If the arc were not in equilibrium, it follows that the probe was not in an arc path at the extremities of the flame but interrupted these paths as it moved into the stream.

When Eq. (A7) from Appendix A was applied to the data in Fig. 11, it was obvious that

$$\frac{e}{kT} = \bar{S} \tag{1}$$

where $\bar{S}$ is the slope of the curve. From this a value of T can be calculated. Application of Eq. (1) to each curve in Fig. 11 resulted in

$$T_{e_1} \approx 12{,}000°K$$
$$T_{e_2} \approx 18{,}000°K$$
$$T_{e_3} \approx 18{,}000°K$$

where T_{e_1}, T_{e_2}, and T_{e_3} are electron temperatures calculated from curves 1, 2, and 3, respectively. These values are electron temperatures and are in close agreement with gas temperatures found by the spectrometric method (Ref. 2). If it is assumed that the Langmuir probe data yield electron temperatures that are nearly correct, it appears that the spectrometric method of temperature measurement defined in Ref. 2 is not a measurement of gas temperature but, because of the blown arc, is a measurement of electron temperature in the arc channel.

It should be pointed out that the application of Langmuir probe theory to the atmospheric plasma flame is not completely valid. The probe method requires that the mean free path of the gas molecules be long compared with the probe diameter so that the disturbing effect of the probe on the plasma will be negligible. In the atmospheric flame the mean free path is short compared with the probe diameter ($\lambda \approx 10^{-4}$ cm). Therefore, error might well be encountered with this technique. However, the results of the Langmuir probe method imply that at the gas stream extremities there is little disturbing effect by the probe, and the method is useful in defining the location of an arc channel.

The final proof of the validity of the hypothesis in Fig. 4a lies in the increased gas flow experiment. Reference 2 showed that, as the gas flow to the plasma generator was increased, the total electric current decreased. Therefore, when it was found that the probe current actually increased as the gas flow increased and total current decreased, the only explanation was that more arcs were being blown outside the orifice.

LOW PRESSURE

Before discussing the results of the experiment at low pressure, certain observations must be made. The first concerns the relative intensity of the expanded flame as compared with the atmospheric flame or the hot core of the altitude flame. At atmospheric pressure the brilliant bluish plasma flame is of such high intensity that observations with the naked eye are impossible. However, the expanded flame is of relatively low intensity to the eye, light red in color, and partially transparent. This leads to the preliminary conclusion that in the expanded section the blown arc does not exist. The second observation refers to that section called the hot core (Fig. 14). The blown arc might well be established in this section because of the extremely high light intensity present. Therefore, for testing at low pressure two parts of the flame must be discussed, the hot core and the expanded flame.

The results of the current probe studies indicated that the expanded plasma flame behaved as a highly conductive medium but did not behave as an arc would be expected to. This was shown by the very nearly constant current that could be detected when the probe in Fig. 3b was placed anywhere in the stream. Also, the very small current that could be detected with the probe in Fig. 3a indicated that arc currents were probably not present. However, when the probe was inserted in the hot core of the jet, high currents could be measured just as in the case of the atmospheric jet.

Application of the double probe technique, Schematic VI, to the expanded flame gave even more support to the theory that the blown arc is contained only in the hot core. When the double probe traversed the expanded flame (outside the hot core), the potential between the probes (Fig. 15) was always in the same direction, away from the orifice, and increased as the probe was moved toward the extremities of the flame. Data were obtained at planes of measurement one inch apart up to a distance of 10 in. downstream. In every case, the data were similar to the typical data shown in Fig. 6. A reversal of potential drop could not be detected at any point in the expanded flame.

It remains to explain why, if the double probe is not interrupting arc paths, the two probes have a difference of potential. Recombination of the gas components occurs as they move downstream. Therefore, moving downstream there is a loss of total potential energy of any cross section of the stream. Because the electrons have a much higher mobility than the ions and neutral atoms, the current through the voltage measuring device is electron current, and there are more electrons impinging on the upstream probe than on the downstream probe. Thus there is a difference of potential between the probes.

When the double probe was passed through the hot core of the expanded jet, it was found that the polarity reversed many times, an indication that the blown arc existed in the hot core but was not blown any farther downstream in the expanded jet than in the atmospheric jet.

The Langmuir probe circuit, when applied to the low pressure plasma jet, was of prime interest. At a test cell pressure of 0.55 mm Hg, the mean free path of the gas components was approximately equal to the effective probe diameter ($\lambda \approx 0.6$ cm), and therefore the disturbing effect of the probe was small. When the probe was immersed in the hot core at the orifice exit, the data (Fig. 17, Curve 1) were not in agreement with the theory, and the deviation from a Maxwellian distribution indicated nonequilibrium or blown arcs. The electron temperature calculated from this curve was 37, 800°K, which is not a reasonable value for the electron temperature of an equilibrium gas. At a position 4 in. downstream, the data (Fig. 17, Curve 2) agreed very well with theory and yielded an electron temperature of 9, 300°K. Curve 3, although taken 4 in. downstream, was at flame edge. Here again the result was unstable, and a Maxwellian distribution of electrons could not be established; the temperature calculation gave 14, 600°K. The probe in the stream center 6 in. downstream yielded good data, and an electron temperature of 6, 500°K was calculated. From this it was concluded that the Langmuir probe in the expanded stream will define the areas where the electrons have a Maxwellian distribution and the areas of nonequilibrium blown arcs.

CONCLUSIONS

ATMOSPHERIC PRESSURE

The addition of energy to the gas stream in the Gerdien-type plasma generator is not, in itself, an equilibrium process. For the gas stream to achieve an equilibrium condition, it must be out of the area of energy addition. In the d-c arc-excited plasma generator at Arnold Center, the arc is blown outside the orifice (when exhausting to atmosphere); thus part of the addition of energy to the gas takes place outside the orifice. The observed plasma flame is in reality, then, the envelope of many blown arcs. Since the blown arcs contribute most of the electromagnetic radiation from the flame, equilibrium dependent methods of temperature measurement using this radiation would be in error.

LOW PRESSURE

The plasma generator exhausting to low pressure produces the expanded flame and a hot core. The hot core is the blown arc envelope and is a nonequilibrium arc discharge very similar to the atmospheric jet. The expanded flame (or ionized gas stream) is in the inner part, probably in equilibrium, and current-free in the electrical sense. There is a flow of high energy electrons in the expanded stream which is the result of collisions and ionization but no current flow caused by an electric potential.

The studies made utilizing the theory set forth by Langmuir show that there exists a Maxwellian distribution of electron velocities in the expanded flame and this infers the possibility of equilibrium. The expanded flame should therefore serve well for studies into the kinetics of hot gases.

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APPENDIX A

THEORY OF THE LANGMUIR PROBE

If the probe in Fig. A1 is considered to be immersed in the plasma between the anode and cathode of the gas discharge tube (Refs. 9, 10, 11, 12, and 13), the probe potential, with respect to the anode, can be varied from $-V_B/2$ to $+V_B/2$, and the corresponding probe current can be measured. The graph in Fig. A2 is an example of the distribution of electric current to the probe obtained when the probe potential is varied. In the region "ab" of the curve in Fig. A2, the probe is a reflector of electrons, and a positive ion, space-charge-limited current flows to the probe. At point b on the curve the faster electrons begin reaching the probe, and as the probe potential decreases still further the ion current to the probe decreases until at point c electrons and ions are arriving at the probe in equal numbers. At point d the probe is at plasma potential, and total electron and ion current is being collected. Therefore, from the theory set forth by Langmuir (Ref. 10) the section of the curve "bcd" may give information as to the distribution of electron velocities in the plasma.

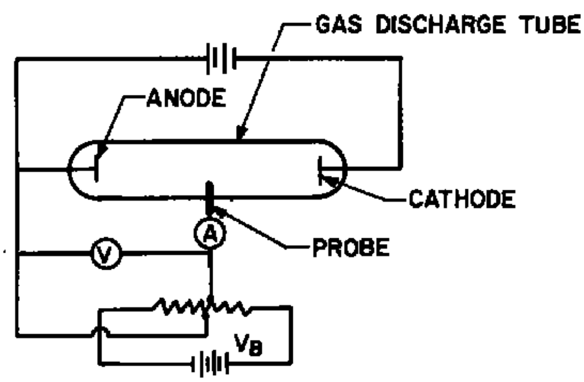


Fig. A1 Gas Discharge Tube and Circuit for Probe Analysis

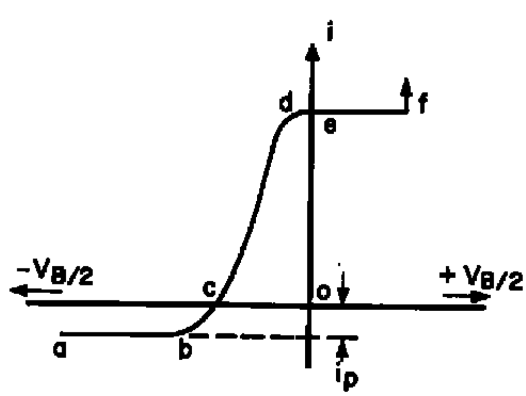


Fig. A2 Variation in Probe Current with Changes in Probe Potential

To show how the curve "bcd" may give this information, consider the following argument. In an equilibrium situation (a Maxwellian gas), the ratio of the number density of particles in one region to the number density in another region with a difference of potential between the two regions is given by the Maxwell-Boltzmann distribution, that is, the equilibrium solution of the Boltzmann integrodifferential equation,

$$\frac{N_1}{N_2} = \exp - \frac{E}{kT} \qquad \text{(A1)}$$

where N_1 and N_2 are the number density of particles in each region, E is the work required to move a particle from one region to the other, k is Boltzmann's constant, and T is the absolute temperature. If the particles are considered to be electrons and the potential between the region is V volts then

$$E = -Ve \tag{A2}$$

and Eq. (A1) becomes

$$\frac{N_1}{N_2} = \exp \frac{eV}{kT} \tag{A3}$$

Current density is given by

$$J = \frac{I}{A} = ne\bar{v} \tag{A4}$$

where I is the current in amperes, A is the cross-sectional area of the conductor, n is the number density of electrons, e is the electronic charge, and $\bar{v}$ is the average random electron velocity. The application of Eq. (A4) to Eq. (A3) yields

$$\frac{J_1}{J_2} = \exp \frac{eV}{kT} \tag{A5}$$

and, if J_1 is the current density of the probe and J_2 is the current density of the plasma, then

$$J_{es} = J_{ep} \exp \frac{eV}{kT} \tag{A6}$$

If the natural logarithm of Eq. (A6) is taken, the result is

$$\ln J_{es} = \ln J_{ep} + \frac{eV}{kT} \tag{A7}$$

Equation (A7) provides a means by which the existence of equilibrium in the plasma can be established. Consider the graph in Fig. A3. Here the logarithm of probe current density as a function of probe potential is illustrated using data from the circuit shown in Fig. A1. The points, bd, on the typical graph (Fig. A3) correspond to the points, bd, in Fig. A2. Therefore, since in the region "bd" the plot is a straight line, Eq. (A7) is satisfied, and the existence of a Maxwellian distribution of electrons is established.

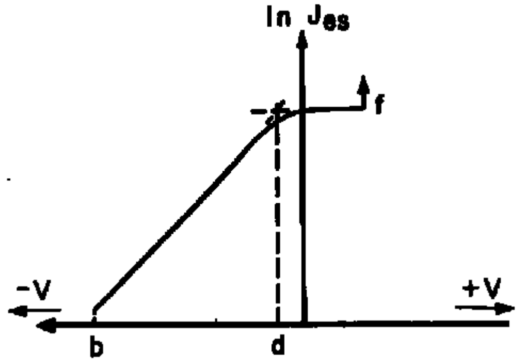


Fig. A3 Logarithm of Probe Current Density as a Function of Probe Potential

The slope of the curve in the region "bd" can readily be measured. Also from Eq. (A7)

$$\frac{e}{kT_e} = S$$

where S is the measured slope. This allows calculation of the electron temperature, T_e, in that the values of the constants e and k are known. For a more complete analysis of the theory of the Langmuir probe, see Refs. 10 and 12.

TABLE 1

DISTRIBUTION OF CURRENT IN PLASMA JET CIRCUIT WITH PROBE IMMERSED IN PLASMA STREAM

AMMETER 1 ±0.5 amp	AMMETER 2 ±0.5 amp	AMMETERS 1 + 2 ±0.5 amp	AMMETER 3 ±0.5 amp	DISTANCE FROM ORIFICE EXIT. in.
0	179.0	179.0	174.0	
8.00	171.8	179.8	180.3	0.13
6.40	175.0	181.4	181.4	0.19
5.00	177.3	182.3	182.3	0.25
3.60	179.2	182.8	182.6	0.31
2.30	180.5	182.5	182.5	0.38
1.20	181.0	182.2	181.9	0.44
0.80	182.5	183.3	183.0	0.50
0.60	182.5	183.1	182.6	0.56
0.30	183.0	183.3	182.8	0.63
0.10	183.2	183.3	182.9	0.69
0.04	183.5	183.54	183.0	0.75

TABLE 2*

DISTRIBUTION OF CURRENT IN EXPANDED PLASMA FLAME

	1/8	1 1/8	2 1/8	3 1/8	4 1/8	5 1/8	6 1/8	7 1/8	8 1/8	9 1/8	10 1/8	11 1/8	12 1/8
Stream Edge		56	14	28	10†	15	15	10	8	6	4	3	2
1/4 Into Stream		220	120	80	100†	65	58	50	28	22	12	12	7
Center	1000	110	80	65	210†	100	75	60	40	34	22	18	14

*The table shows probe current in milliamperes as a function of distance downstream (horizontal headings) and probe position in the gas stream (vertical headings).

†Location of normal shock wave

TABLE 3

DISTRIBUTION OF CURRENT IN PLASMA JET CIRCUIT AT LOW PRESSURE WITH PROBE IMMERSED IN PLASMA STREAM

AMMETER 1 ±0.5 amp	AMMETER 2 ±0.5 amp	AMMETER (1 + 2) ±0.5 amp	AMMETER 3 ±0.5 amp	DISTANCE FROM ORIFICE EXIT, in.
4.0	157.4	161.4	162.0	0.1
4.0	157.4	161.4	162.0	1.0
3.8	157.8	161.6	162.0	2.0
3.8	157.8	161.6	162.0	10.0

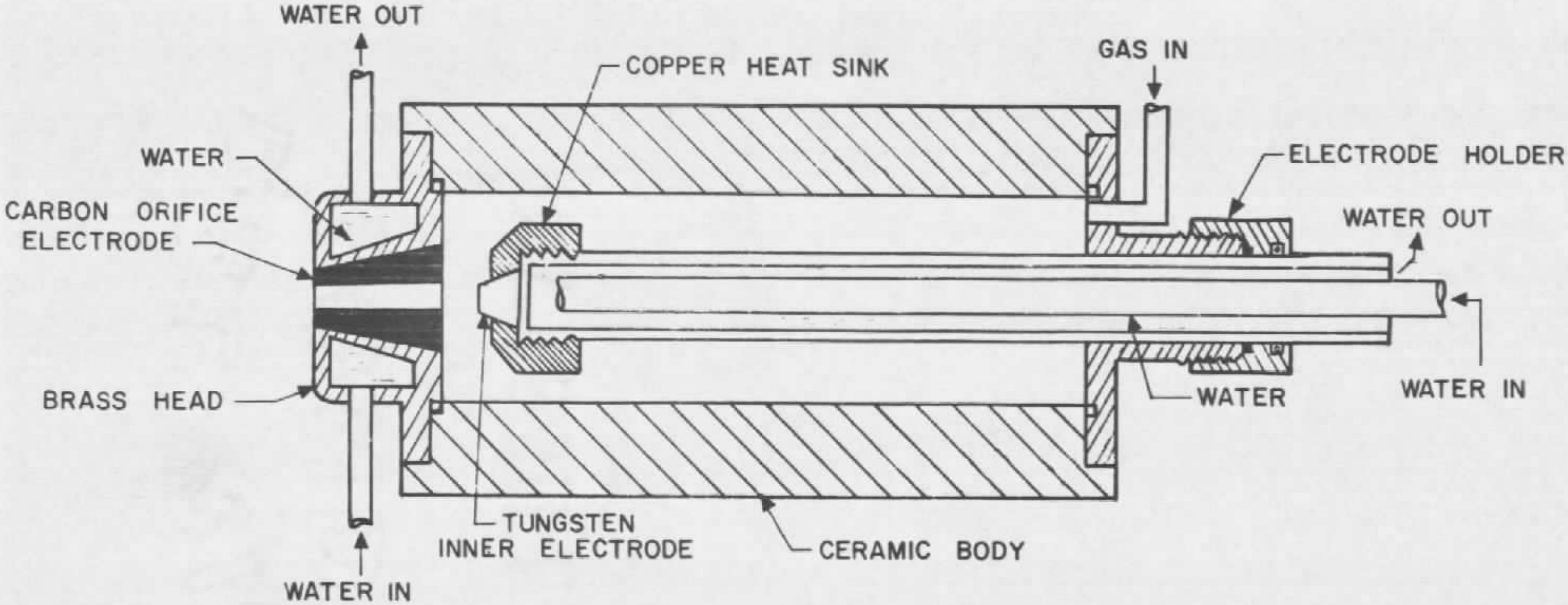


Fig. 1 Cross Section of Plasma Generator

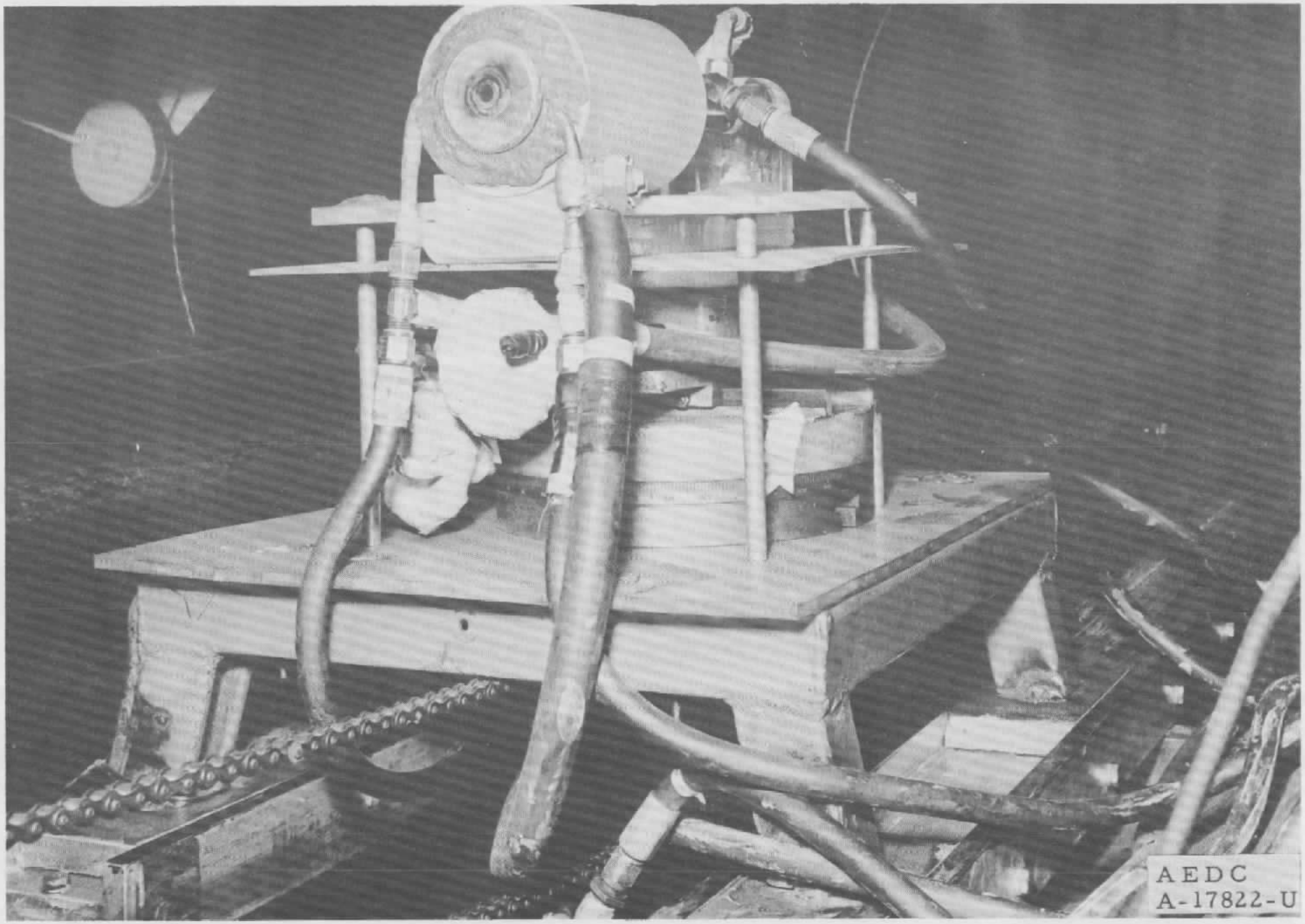


Fig. 2 Photograph of Plasma Generator

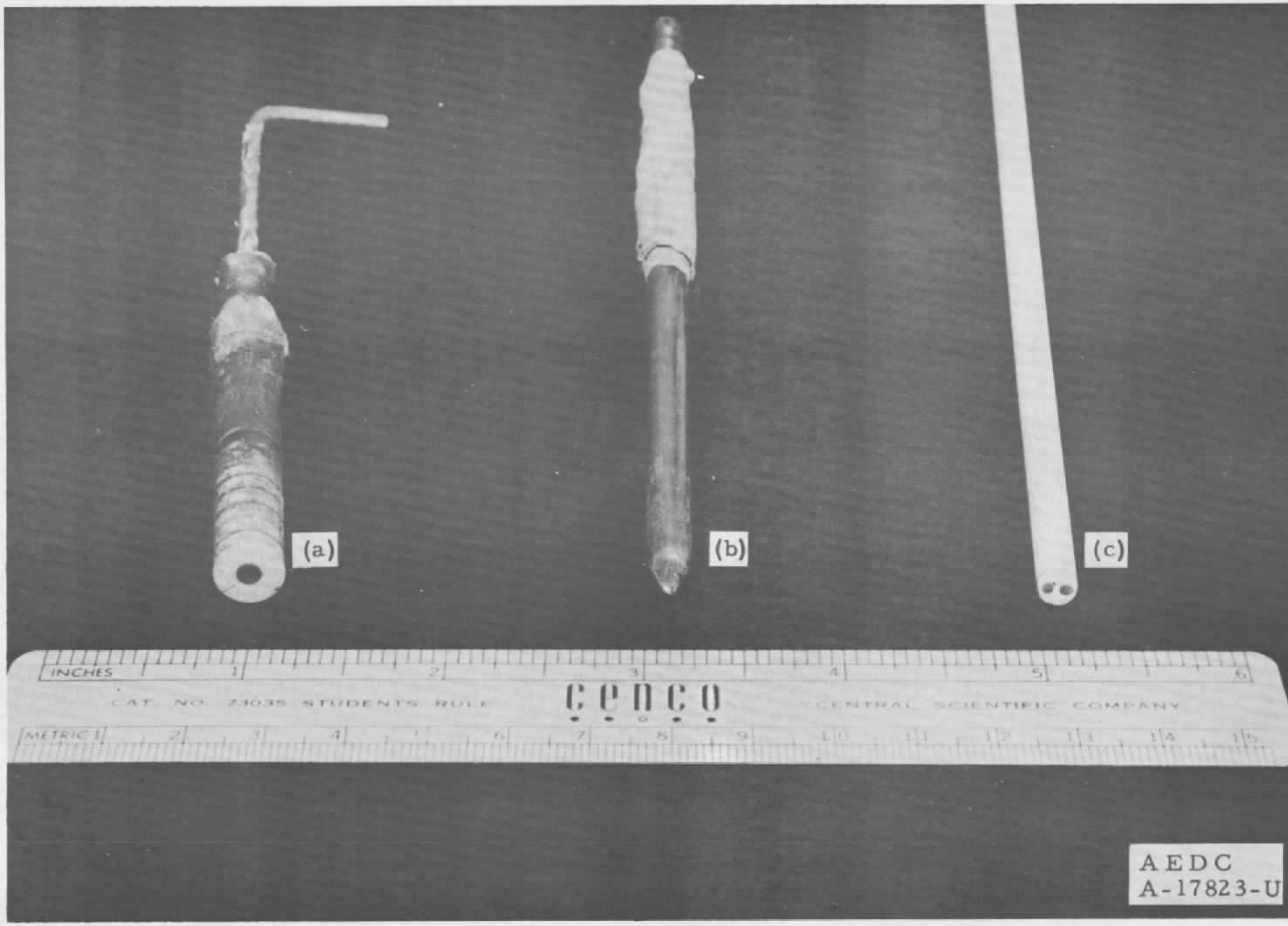
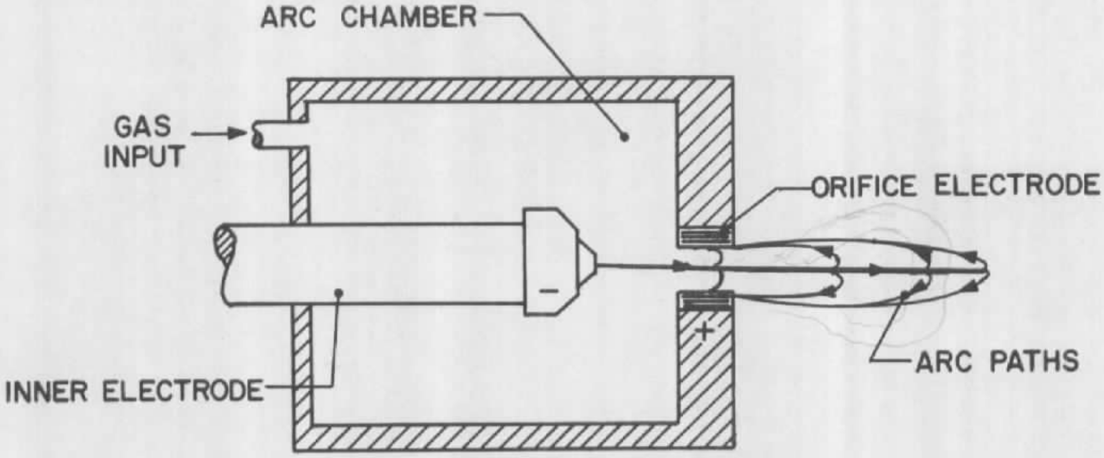
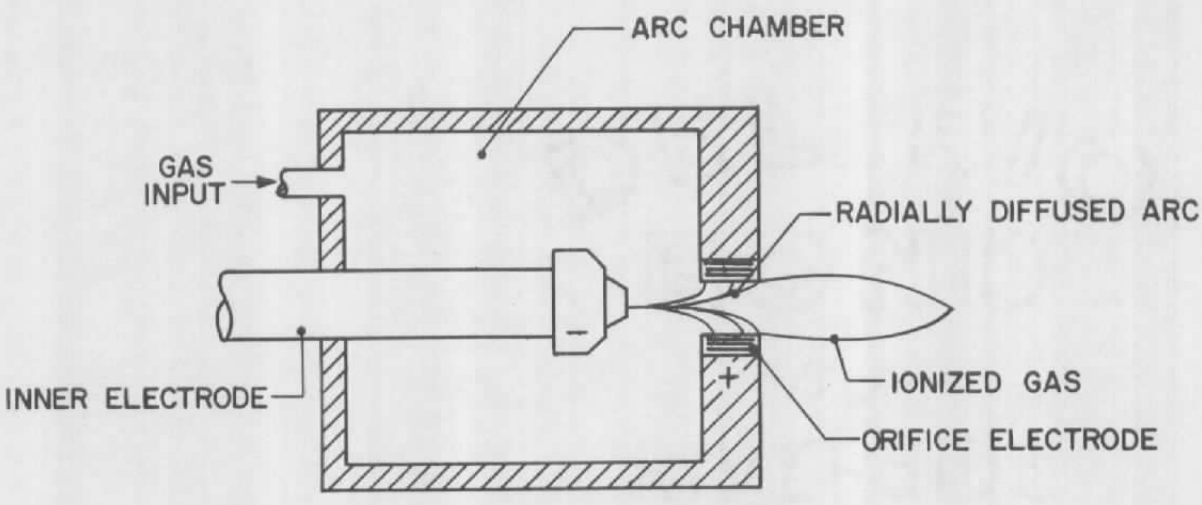


Fig. 3 Photograph of Electrical Probes



a. External Current Paths



b. Radial Diffusion of Current

Fig. 4 Possible Arc Configurations in Gerdien-Type Plasma Jet

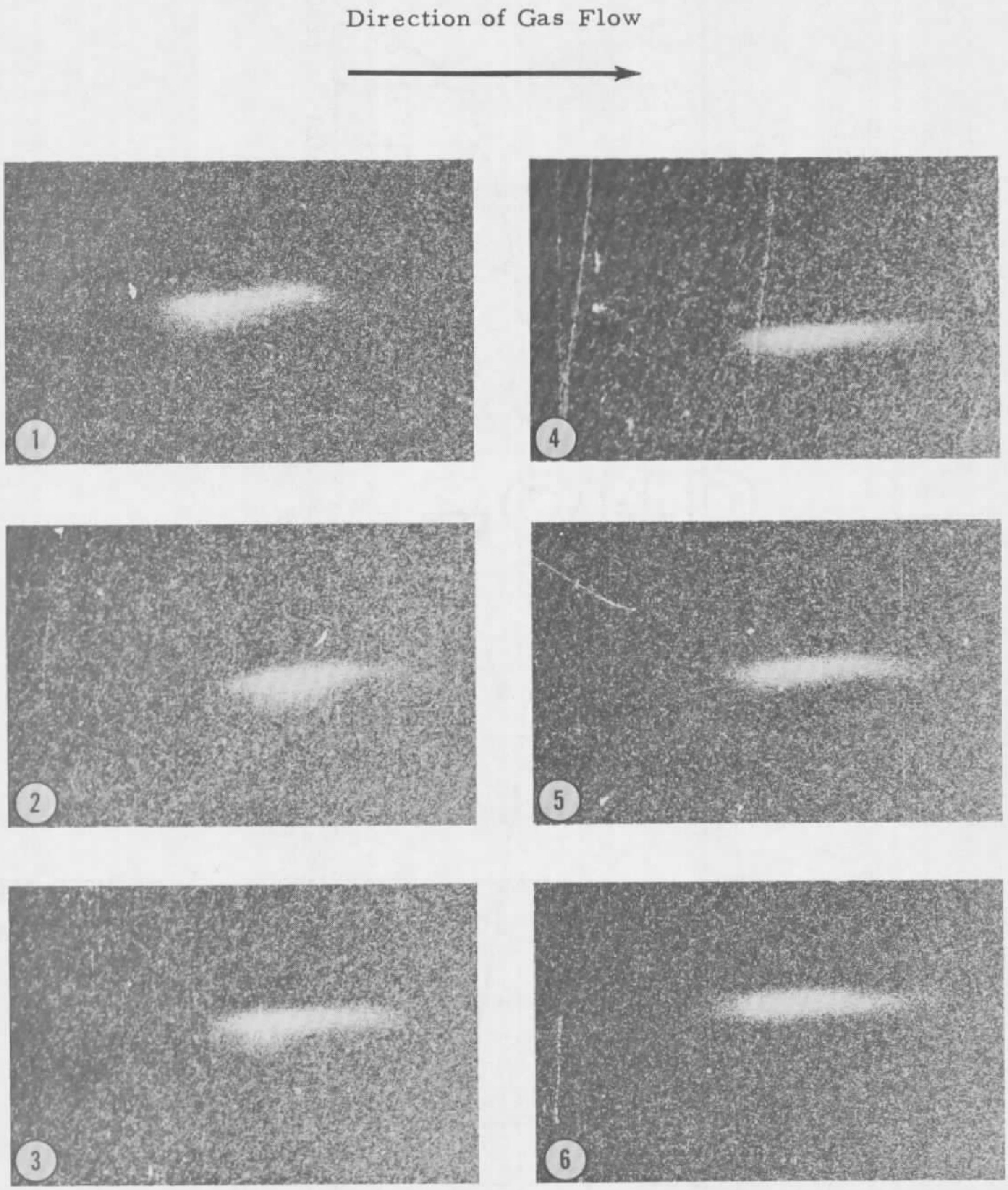


Fig. 5 Sequence of Pictures of Plasma Flame (Taken at 565,000 fps)

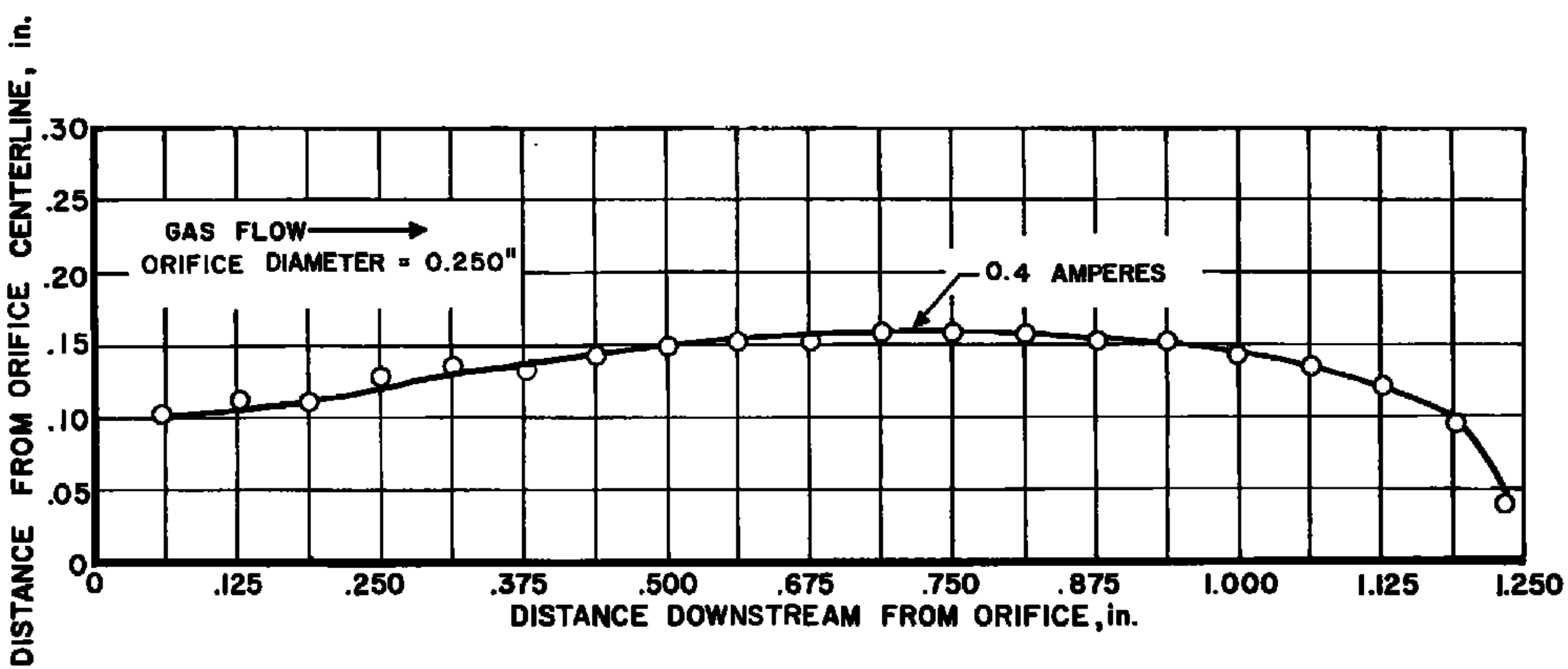


Fig. 6 Contour Curve of Constant Probe Current

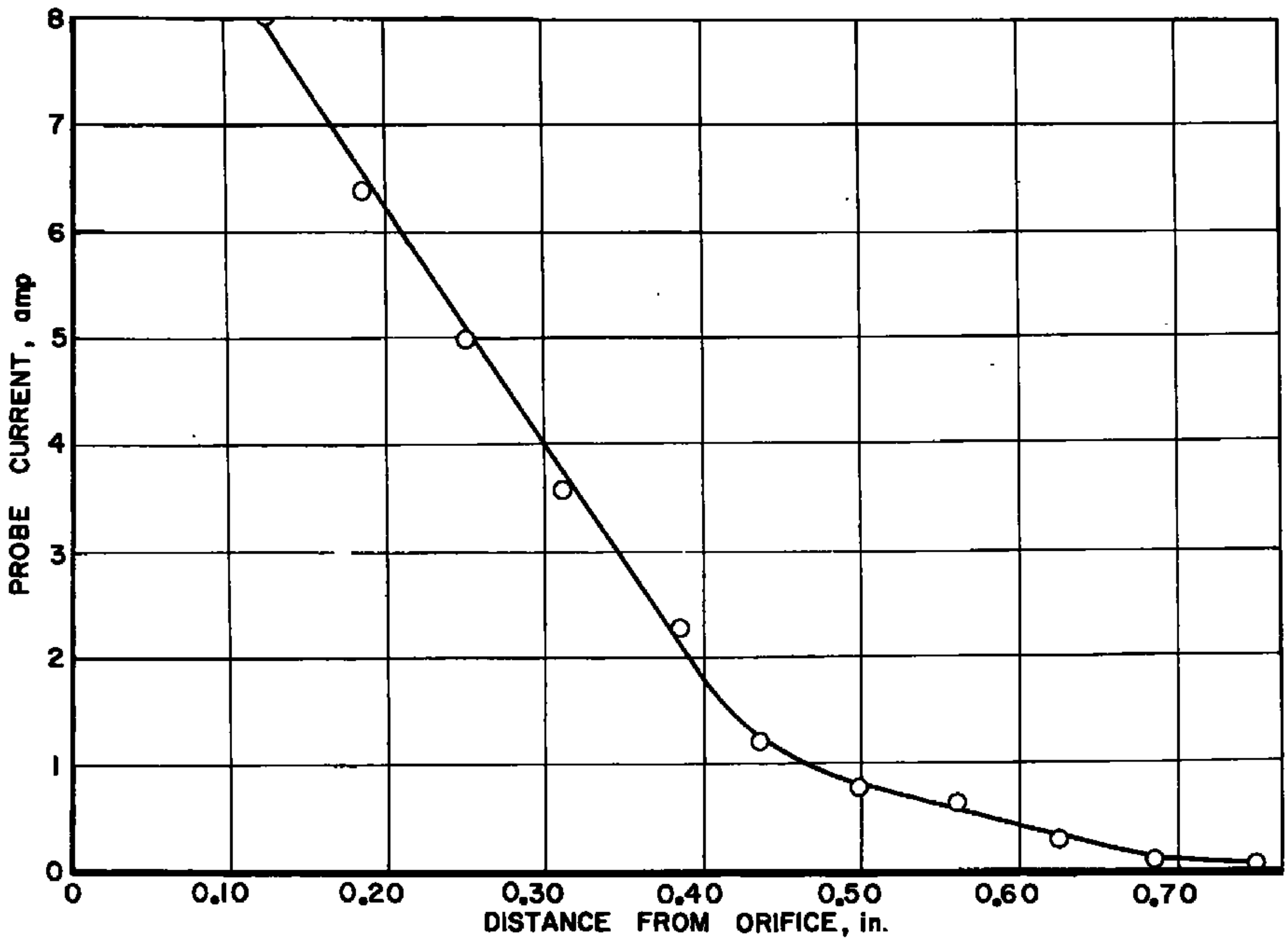
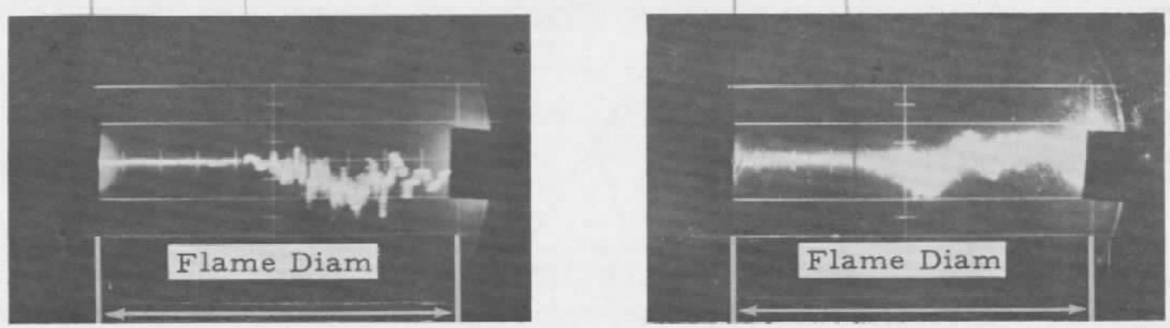


Fig. 7 Variation in Probe Current with Probe Movement Downstream

2. 2.

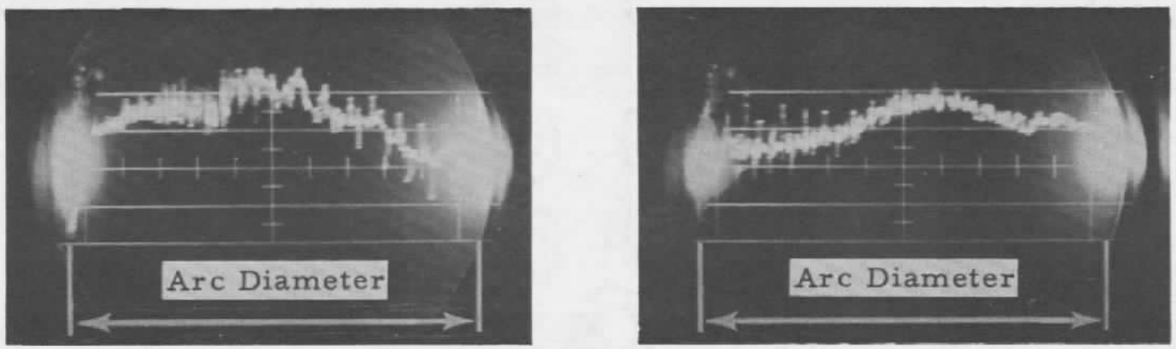


a. 0.5 sec. Trace. Two Volts Peak to Peak Full Scale

b. 2.0 sec. Trace. Two Volts Peak to Peak Full Scale

Fig. 8 Oscilloscope Traces from Double Probe Immersed in Plasma Flame

Which is the traversing direction?
What do the long stretches without marked deflection mean? This effect not noticeable in Fig 9.



a. Two Volts Peak to Peak Full Scale

b. One Volt Peak to Peak Full Scale

Fig. 9 Oscilloscope Traces from Double Probe Immersed in Arc Discharge

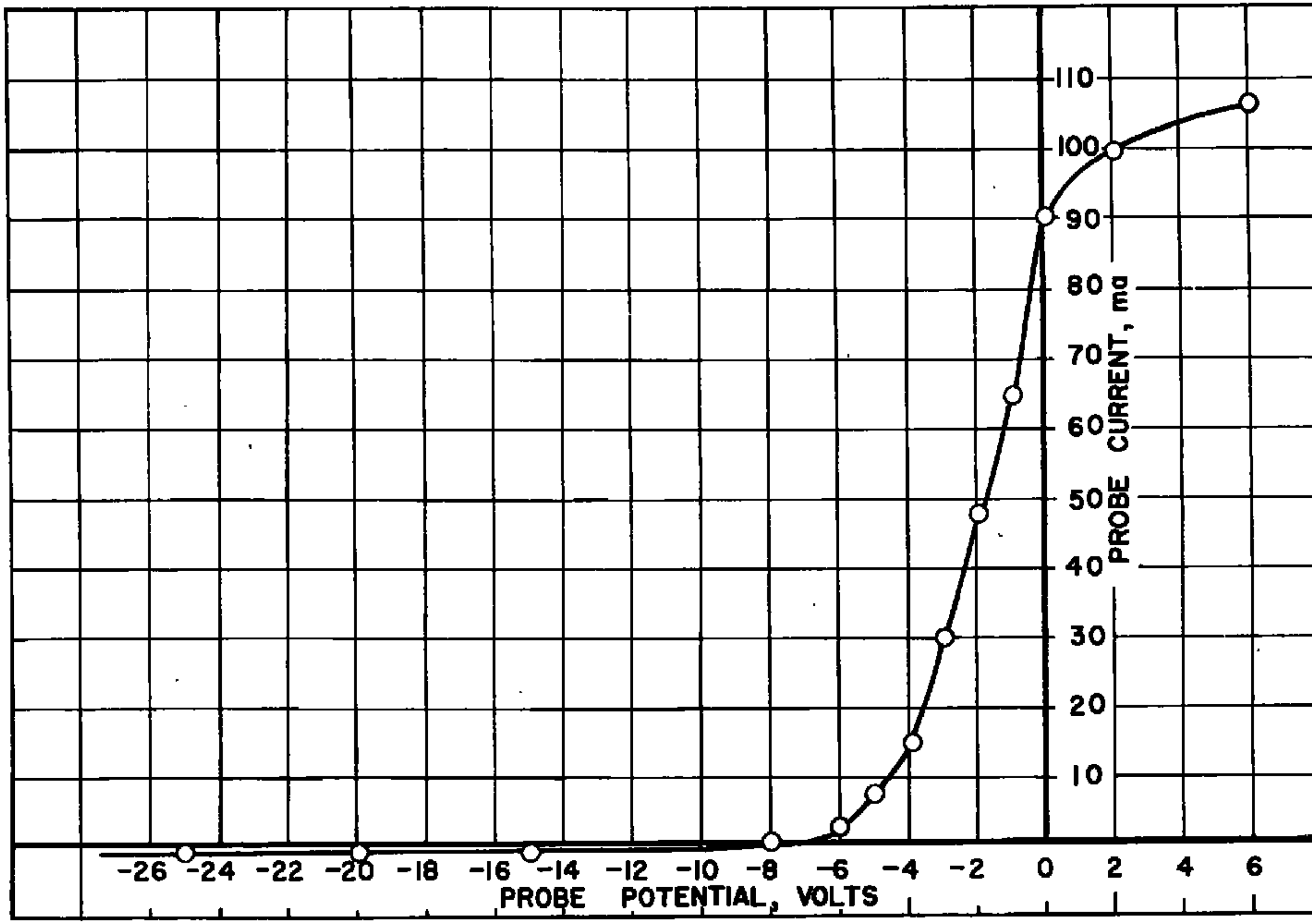


Fig. 10 Variation in Probe Current as Probe Potential Varies

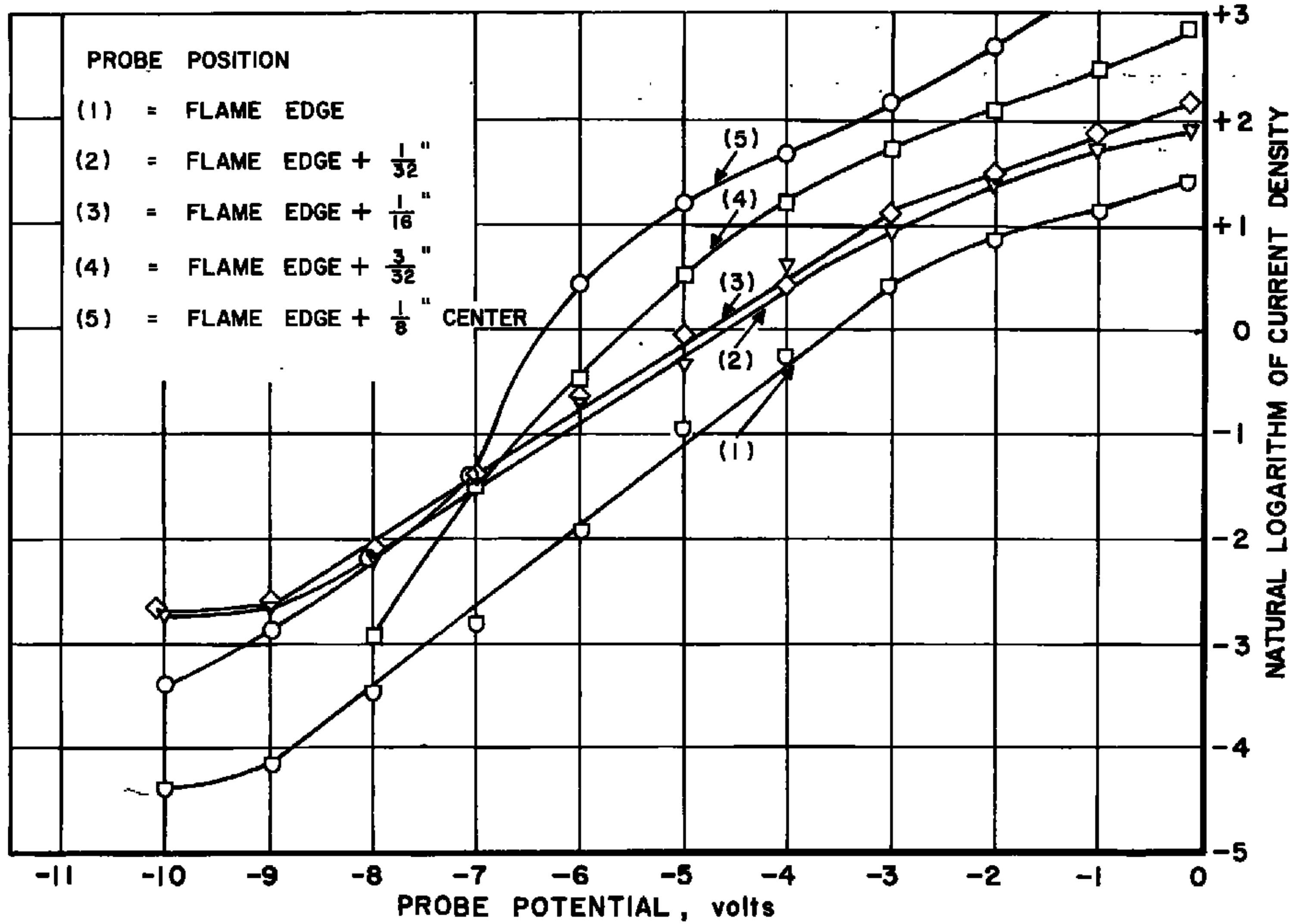
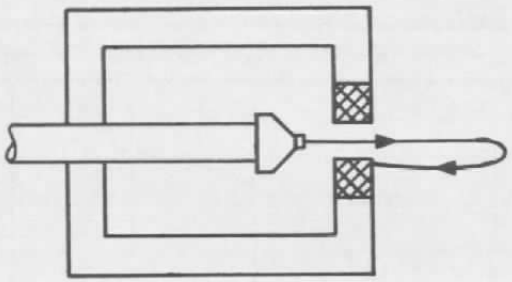
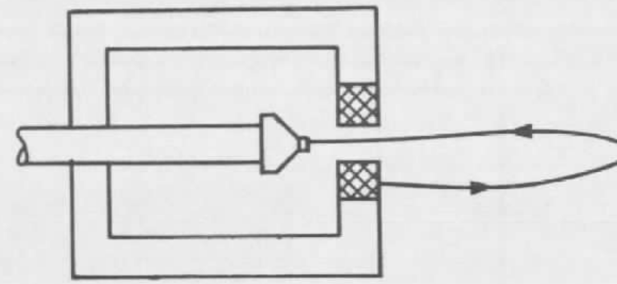


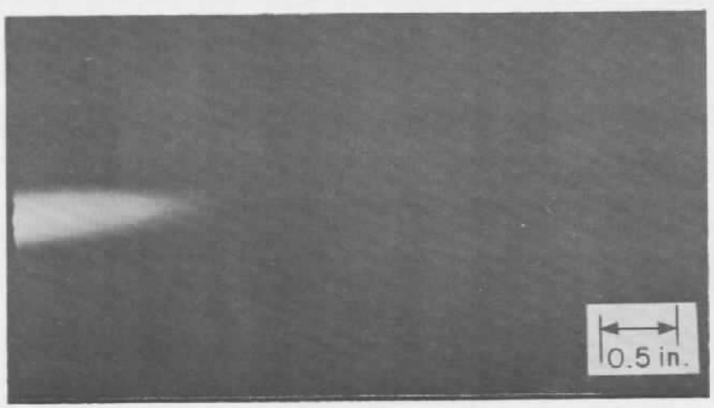
Fig. 11 Langmuir Probe Data for the Atmospheric Jet



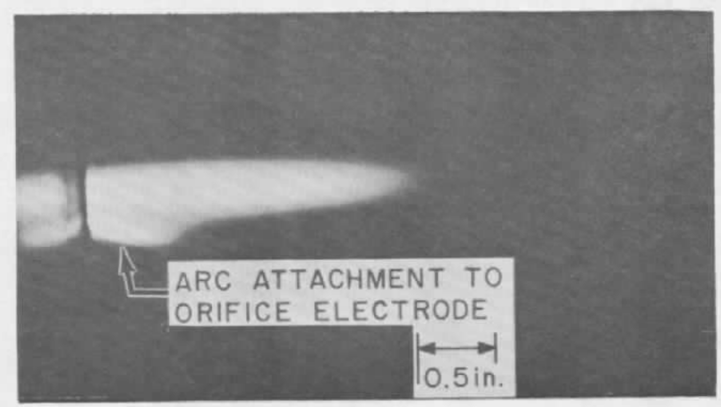
a. Schematic of Current Flow



b. Schematic of Current Flow



a. Orifice Electrode Positive



b. Orifice Electrode Negative

Fig. 12 Photographs of Plasma Jet Operating with Different Orifice Electrode Polarities

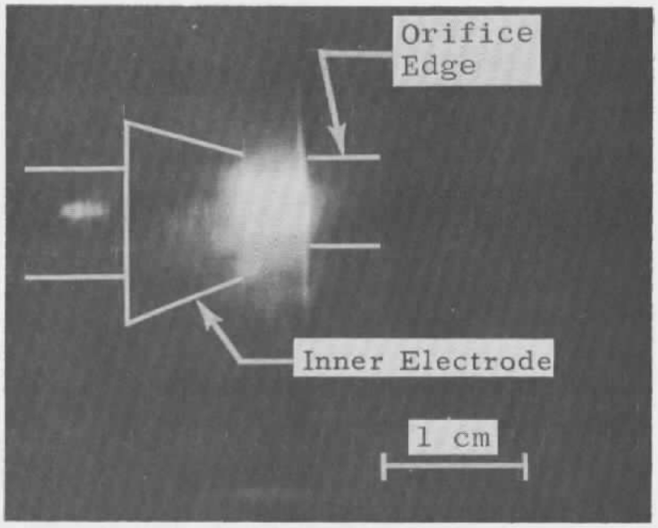


Fig. 13 Photograph of Internal Arc of Plasma Jet

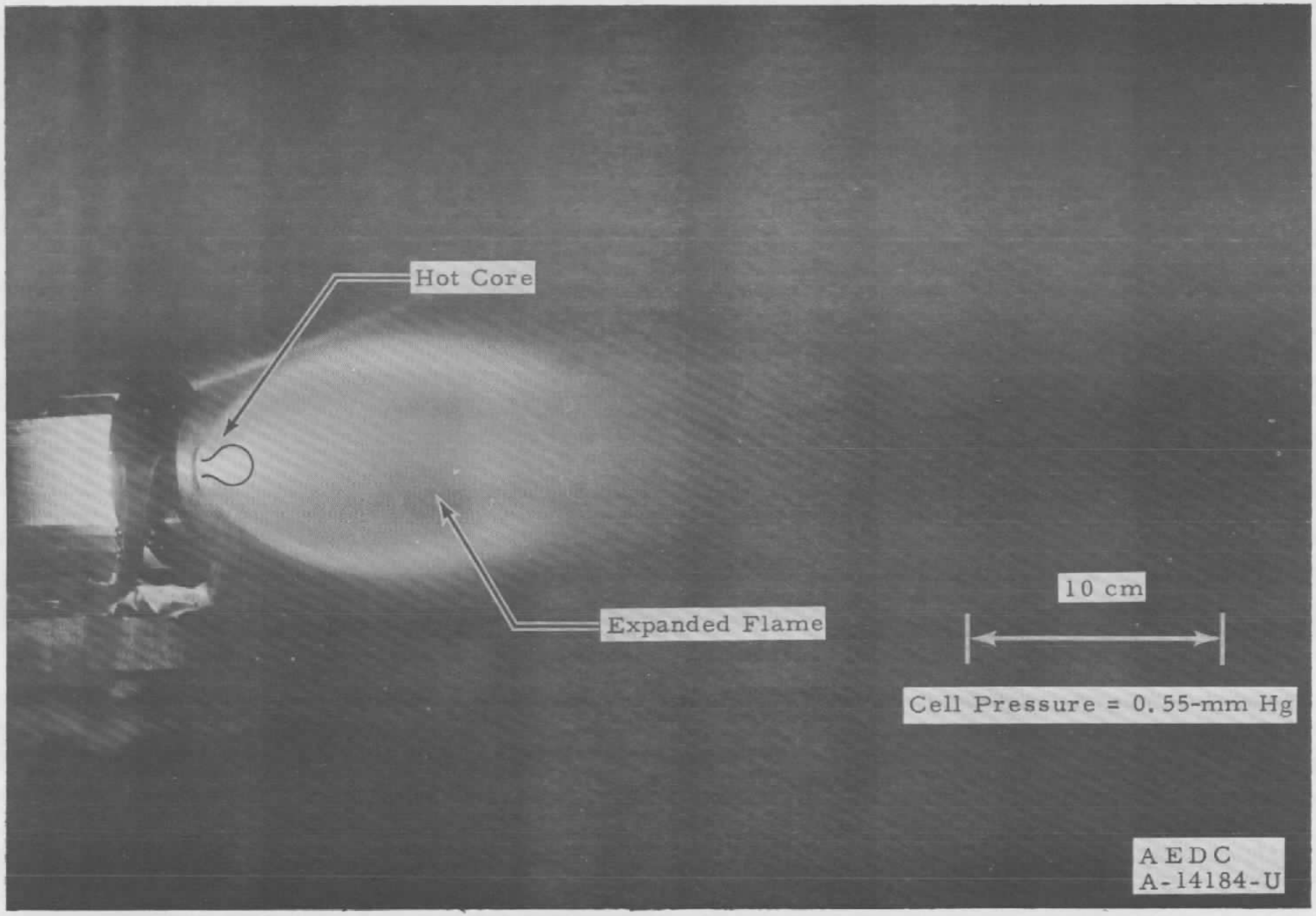


Fig. 14 Plasma Generator Exhausting to Low Pressure

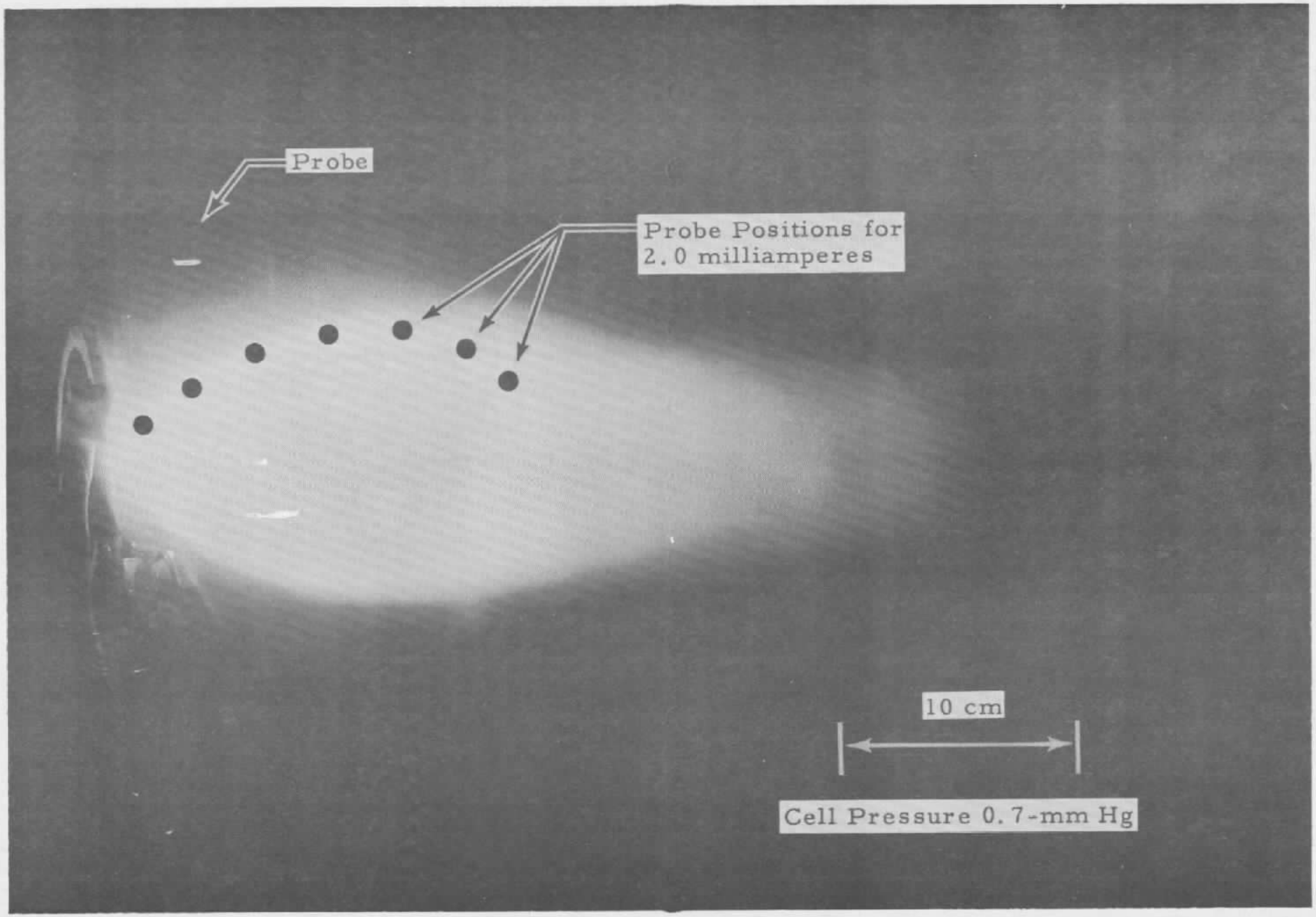


Fig. 15 Plasma Flame with Contour Curve of Constant Probe Current

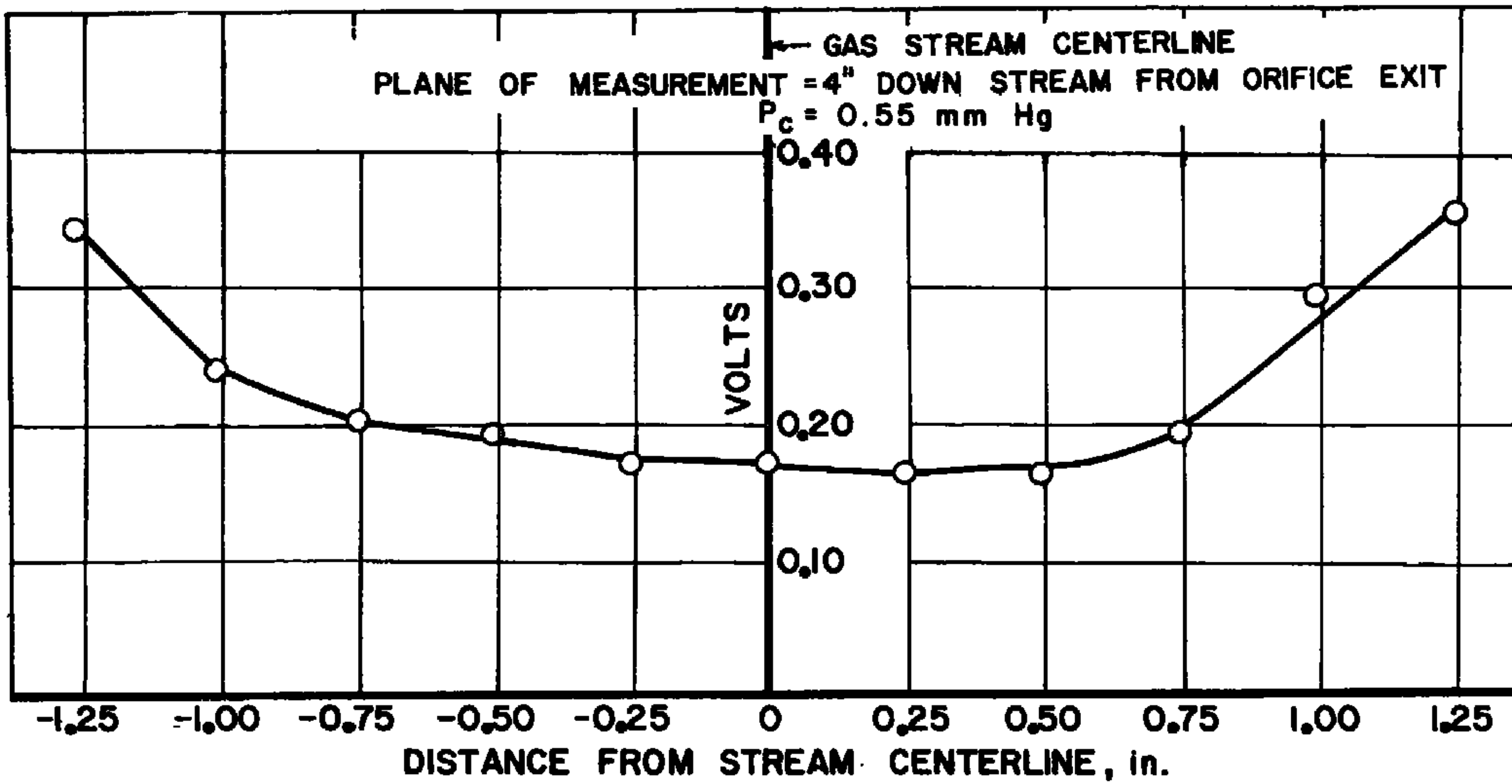


Fig. 16 Double Probe Potential Moving across Expanded Plasma Flame

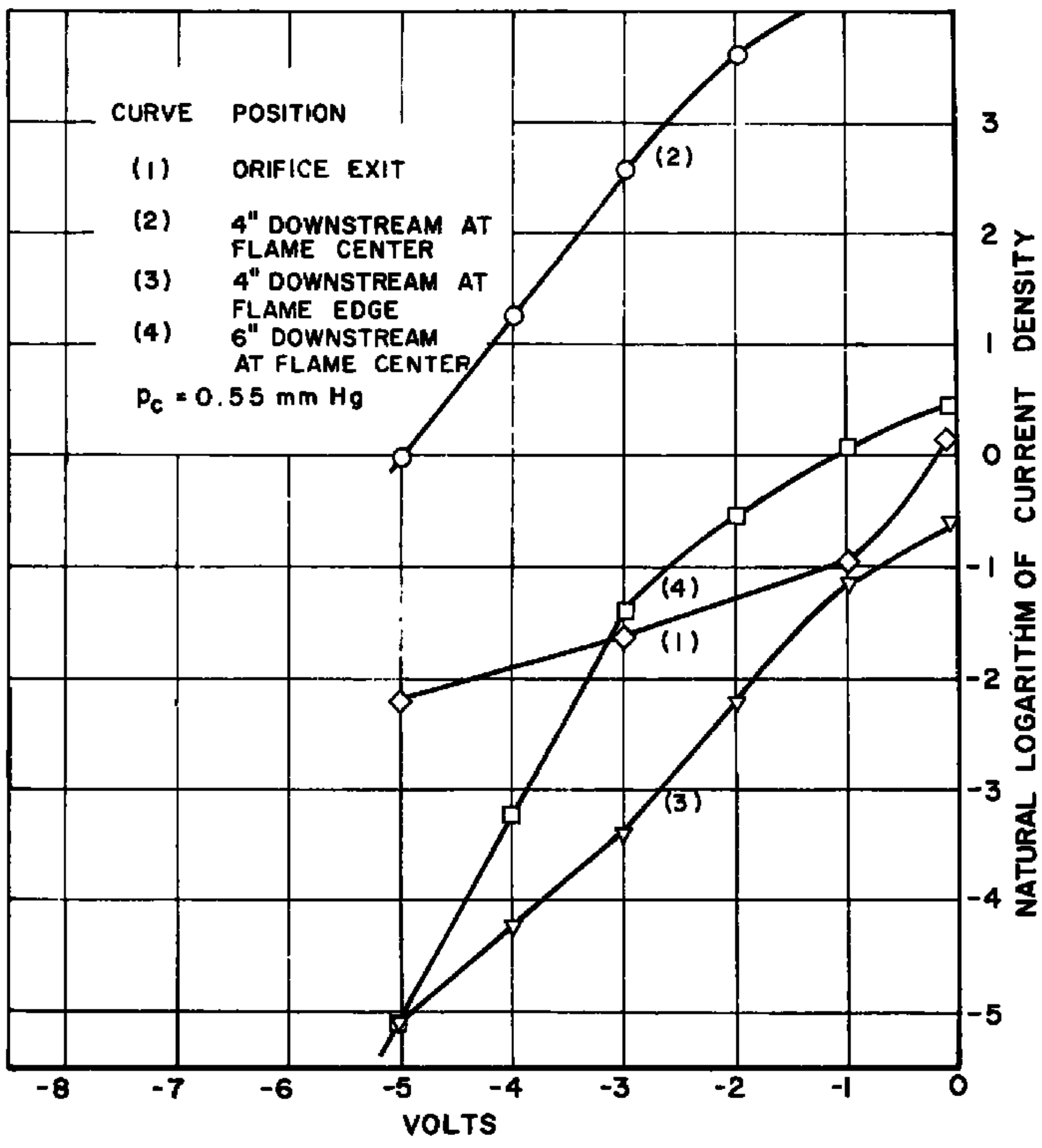
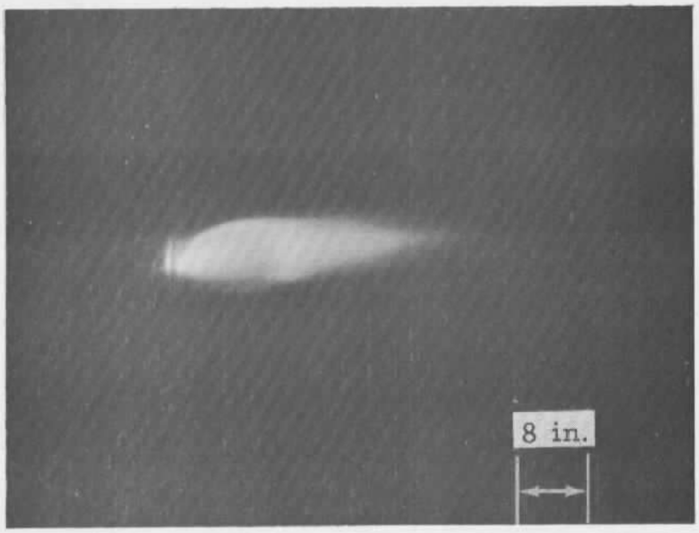
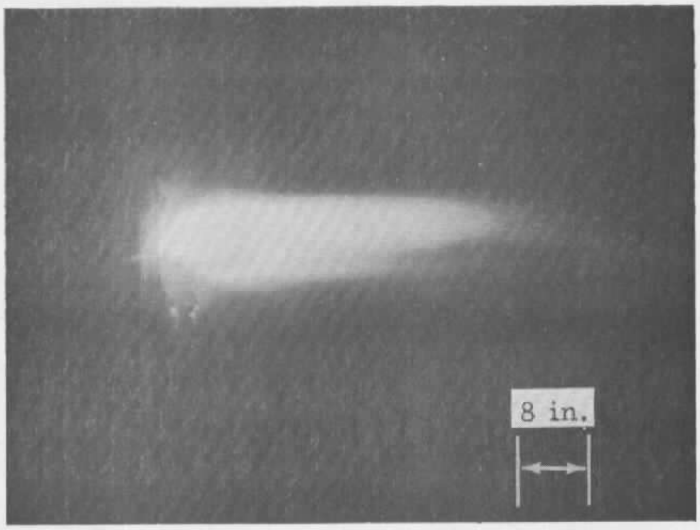


Fig. 17 Langmuir Probe Data for the Expanded Jet



a. Orifice Electrode Polarity Positive



b. Orifice Electrode Polarity Negative

Fig. 18 Photographs of Expanded Plasma Flame Operating with Different Orifice Electrode Polarities

Cut on broken line

AEDC-TR-61-13

UNCLASSIFIED

Arnold Engineering Development Center, ARO, Inc., Arnold Air Force Station, Tennessee
CHARACTERISTICS OF THE ARC IN A GERDIEN-TYPE PLASMA GENERATOR by M. T. Dooley, W. K. McGregor, and L. E. Brewer, December 1961. 54 pp. (ARO Project No. 150927) (Program Area 806A, Project 8951, Task 89104) (AEDC-TR-61-13) (Contract No. AF 40(600)-800 S/A 24(61-73)). Unclassified

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1. Arc plasma generators
2. Gas ionization
3. Gases--Spectroscopy
4. Plasma jets--Electrical properties

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III. Brewer, L. E.

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